International Journal of Ambient Energy

ISSN: (Print) (Online) Journal homepage: https://www.tandfonline.com/loi/taen20

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To cite this article: Douglas Yeboah, Silas Abaidoo Quainoo & Anna Wilma Brew (2023) Hybrid electricity generation using solar energy and kinetic energy of players' footsteps – a case study: Tarkwa Akoon soccer park, Ghana, International Journal of Ambient Energy, 44:1, 2347-2361, DOI: 10.1080/01430750.2023.2235342

To link to this article: https://doi.org/10.1080/01430750.2023.2235342

Published online: 26 Jul 2023.

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INTERNATIONAL JOURNAL OF AMBIENT ENERGY
2023, VOL. 44, NO. 1, 2347–2361
https://doi.org/10.1080/01430750.2023.2235342

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Hybrid electricity generation using solar energy and kinetic energy of players' footsteps – a case study: Tarkwa Akoon soccer park, Ghana

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ABSTRACT

This paper presents the design of a hybrid energy system that incorporates solar photovoltaic (PV) and piezoelectric technologies, using solar energy and kinetic energy from players' footsteps, taking into account the Tarkwa Akoon Soccer Park located in Ghana. A theoretical study of the energy generated and the energy savings utilizing either a single technology or a combination of both technologies is conducted. It is found that the piezoelectric alone can generate 27 MWh of energy, considering the entire 22 players on the pitch, while solar PV generates 13.26 kWh of energy. The installation of piezoelectric tiles at the pitch entrance can generate about 210 kWh of energy from the footsteps of 10,000 spectators. In terms of energy savings, using solar PV together with piezoelectric technology to generate energy from players' and spectators' footsteps gave substantially higher energy savings of 99.94% and 89.75%, respectively, compared to zero or minimal energy savings associated with solar PV alone. The analysis reveals that piezoelectric tiles can still produce maximum energy with minimal solar panel use, making this sustainable technology ideal for high-foot-traffic areas. Implementing this technology can improve energy efficiency, reduce global energy demand, and mitigate the effects of global warming.

ARTICLE HISTORY
Received 27 October 2022
Accepted 28 March 2023

KEYWORDS
High foot traffic; photovoltaic; piezoelectric tiles; energy generation; high energy demand; greenhouse gas

1. Introduction

In recent years, most developing countries around the world have experienced rampant power outages due to the increasing demand for electricity (Avtar et al. 2019). For instance, in Ghana, despite a comparatively huge electricity access rate, just 42% of the residents connected to the grid enjoy a reliable electricity supply (Acheampong and Menyeh 2021). This implies that in the future, the impact of power outages will be more severe as it is anticipated that more activities will rely hugely on electricity (Casey et al. 2020; Hanna and Marqusee 2022). This strikes us to delve in the direction of generating and harnessing energy whether commercially or industrially in more clean, resourceful, and reliable ways. A step in that direction is by incorporating renewable energy systems into our daily power generation.

The utilisation of renewable sources for sustainable power production coupled with low emissions depends on available resources, which could be in the form of biomass energy, solar energy, wind energy, hydropower, geothermal energy, kinetic energy, etc (Gbadamosi et al. 2022; Mutezo and Mulopo 2021). Although these renewable energy sources are considered advanced for electricity production, one challenge associated with them is variational and unpredictable climatic behaviour; their accessibility differs based on location. Due to this intermittency, using just a single renewable source may be challenging in terms of electricity generation, and operational costs. A typical example is the generation of electrical energy from a photovoltaic system, which is dependent on irradiance and density of light (Hao et al. 2022). If irradiance in a region is scarce due to atmospheric conditions such as rain, cloudiness, hale, storm or snow, it may hinder electrical energy generation. Consequently, to enhance electricity generation, improve space utilisation efficiency, reduce cost, and ultimately enhance system efficiency (Gbadamosi and Nwulu 2020), two or more renewable energy sources can be put together to form a hybrid renewable energy system (Hoseinzadeh and Garcia 2022; Lawan and Abidin 2020; Mahmoudan et al. 2022). For instance, if solar panels are coupled with wind turbine in a combined system, the resulting hybrid system can produce energy from solar energy and wind energy.

A number of studies have proven that hybrid renewable energy is economically, technically, and environmentally viable for electricity generation worldwide. For instance, Chen et al. (2023) have recently presented a feasible approach and a techno-economic assessment of off-grid hybrid energy systems of 200 residences in three rural islands of Iran, which include Lavan, Larak, and Failaka, using solar photovoltaic (PV) panels, wind turbine, and hydrokinetic turbines. In a related study, Hoseinzadeh and Garcia (2022) have also presented a technical and economic viability analysis of hybrid renewable energy systems in Catania city utilising PV panels, wind turbines, fuel cell, electrolyser, and hydrogen tank to meet the need for 2 MW electricity. It was observed that PV modules and wind turbines are complementary in terms of electricity generation within some months of the year. Also, the feasibility of hybrid renewable energy penetration using solar and wind energy has been analysed for four cities in Iran (Makkiabadi et al. 2020), which include Ahvaz, Sirjan, Neyshabur, and Tabriz. It was deduced herein that utilising wind power in Neyshabur and Tabriz cities, and solar

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energy in Ahvaz and Sirjan cities are reasonable to produce electricity. Similarly, Hoseinzadeh, Ghasemi, and Heyns (2020) have analysed the techno-economic utilisation of hybrid renewable systems consisting of solar and wind energies during hot and dry seasons using the Mashhad Sarrood power plant as a case study.

In addition to assessing the techno-economic and environmental viability, some studies have also systematically investigated the design optimisation of hybrid energy systems focusing on renewable energy resources and energy storage. For instance, Mahmoudan et al. (2022) have presented an investigation into a new hybrid renewable-energy system using geothermal and solar energy for generating several products. Other researchers (Emrani et al. 2022) have proposed the combination of a novel emerging energy storage system called gravity energy storage with hybrid wind and PV modules for an off-grid system to assess its optimal design and operation. Also, Baseer, Alqahtani, and Rehman (2019) have explored the potential of PV-wind-diesel and PV-wind-battery hybrid systems to satisfy the demand of three households in Jubail Industrial City, an eastern coastal city in Saudi Arabia. Furthermore, Murugaperumal, Ajay, and Raj (2019) have presented the validity of optimal design and potential of hybrid systems comprising of solar PV, wind, biomass and battery backup system to meet the load profile of a rural village Korkadu in India. In another study (Cao et al. 2018), inspired by the swaying of lantern in the wind, a hybrid triboelectric-solar energy nanogenerator has been fabricated and is capable of harvesting both wind and solar energy with high efficiency. Moreover, through a comprehensive review, other researchers have reported that hybrid or multi-source energy harvesting is the future of energy harvesting and it has come to stay (Bai, Jantunen, and Juuti 2018).

Energy harvesting characteristics of both piezoelectric tile and solar PV have been in existence for a long time (Siores, Hadimani, and Vatansever 2010; Vatansever, Siores, and Shah 2012), however nowadays more attention has been given to the development of usable materials for electricity production (Safaei, Sodano, and Anton 2019). Piezoelectric tiles can convert practically mechanical energy into electricity (Jintanawan et al. 2019). Also, the advancement in solar PV production as a whole is substantially viable for a sustainable world (Hayat et al. 2019). Solar energy is the energy obtained from the sun's rays reaching the earth's surface. Solar energy can be converted into electricity in two ways; i.e. through the use of photovoltaics for harnessing the light from the sun, and solar power plants which indirectly generate electricity when the heat from solar thermal collectors is used to heat a fluid which produces steam (Hao et al. 2022; Hayat et al. 2019). On the other hand, kinetic energy typically exists in many forms: it can be in the form of vibrations or random impacts, which are ubiquitous in our environment; it can be generated by human activities such as walking or pedestrian flow and vehicle flow; it can also be generated by natural occurrences such as ocean waves and river flows. The ability to generate energy from human movement has greatly increased (Sun, Shang, and Wang 2019). Since it comprises of both kinetic and potential energy from the human body, the energy generated by human locomotion is significantly simpler to capture and convert into usable electricity. The technologies that can be used to convert this wasted ambient kinetic energy into useful electricity, include but are not limited to piezoelectric transducers, electromagnetic transducers, and dielectric elastomers (Jintanawan et al. 2019).

Solar and human kinetic energy can be regarded as the prevalent ambient energy sources that frequently coexist, where harnessing both simultaneously can be extremely useful (Cao et al. 2018). However, few studies have been conducted on hybrid electricity generation using these two energy sources of energy so as to enhance both structural multifunctionality and system-level robustness in energy harvesting. For instance, quite recently, Fujimura et al. (2022) have experimentally proposed a comprehensive piezoelectric-solar PV system that can produce electricity solely from indoor lighting provided by light-emitting diodes and compact fluorescent lamps. Gaikwad et al. (2020) have also presented hybrid electricity generation using piezoelectric tiles and solar PV, which can be used for commercial applications. In another work, Saifan et al. (2019) have presented a novel way of generating electricity utilising solar panels and piezoelectric elements. It was concluded that smart walk can produce the intended power output and has proven to be achievable. The hybrid energy production using solar panels and piezoelectric tangles to run direct current and alternating current DC and AC loads has been successfully deployed (Mahajan et al. 2017). According to Govind et al. (2015), using hybrid power generation with solar and piezoelectric effect energy provides a path for obtaining continuous power generation from renewable energy sources based on weather conditions. Therefore, the hybridisation of both solar PV and piezoelectric tiles technologies will be the focus of future research, since it can generate enough electricity to illuminate a whole sports stadium or soccer pitch, a street, and a neighbouring community.

Sports stadiums are known to be energy-hungry beasts and based on the facilities provided by diverse avenues, for instance, turf heating, heated seating, etc., the quantity of energy usage can change quickly (Keating 2021). For instance, stadium lights consume a huge amount of energy, because when lighting up the park, it is reasonable to meet all the standards. A stadium tends to consume an average of 25,000 kWh of electrical energy, just so viewers can have an epic 90-minute game with no dark cloud, a glitch in telecasting, or absolute darkness on the pitch at the suspenseful moment of a goal or penalty take-out ('How much energy' 2022). Research by Smulders (2012) revealed that more than 4000 stadiums exploit up to 40 TWh/year, which are mainly generated from conventional fossil fuels. A modern medium-sized stadium (55,000 spectators) reaches an energy use of 10,000 MWh/year which equals 3600 tons of CO_2 per year (Dovi et al. 2009). Those said amounts of electricity could equally be distributed elsewhere in the locality to power dozens of homes. In a bid to ease the electricity problems and eventually reduce global warming, it is prudent to combine the kinetic energy of players and solar energy to produce enormous electricity. During a soccer game, an average professional player may sprint between 9.1 to 10.6 km ('World Cup's top physical performances' 2022). This concept has been proven to be an opportunity to utilise the energy of players to power soccer pitches and probably their surroundings in an environmentally friendly manner ('Pavegen brings kinetic power' 2016; 'Pavegen and shell' 2014).

Even though certain countries like Brazil and Nigeria have adopted the hybrid kinetic – solar powered soccer pitch concept ('Pavegen brings kinetic power' 2016; 'Pavegen and shell' 2014), research in this field is still inactive. A critical analysis of the above reviews depicts that there are no studies that considered the optimum generation of electricity from players' footsteps using hybrid piezoelectric tile and solar PV technologies that can be used in large-scale applications. Therefore, this paper presents the design and analysis of large-scale electricity generation system utilising simultaneously solar energy and the kinetic energy of players' movements on a pitch, using the Tarkwa Akoon Soccer pitch located in Ghana as a case study. Herein, an increase in the number of players on the field will greatly enhance the amount of electricity generated. Hence, implementation of this sustainable technology within a sports complex could be the key that facilitates and promotes sustainable development.

2. Materials and methods

2.1. Site assessment

The geographical location of Ghana where Tarkwa Akoon Soccer Park is located has a Ghana Postal Address (GPA) coordinates longitude of 1.993047 degrees West and latitude of 5.301832 degrees North (Ababio, Takyi, and Anto 2021). The Akoon Park was built by Tarkwa Goldfields Ghana limited to assist the home team Medeama Football Club in their premier league matches. The Akoon Park has an area of 100 m $\times$ 55 m $=$ 5500 m^2 of which part of this area is used for the installation of piezoelectric tiles. The average pitch capacity of the Akoon soccer pitch is 10,000. However, the sporting facility has no seating for spectators but has a Very Important Person (VIP) section with a 30-seater capacity with a roofing structure. Figure 1 shows the Tarkwa Akoon soccer park.

Table 1. Solar irradiation data for Tarkwa, Ghana.

Month	Daily Solar Radiation – Horizontal (kWh/m^2/day)
January	4.13
February	5.34
March	5.35
April	3.99
May	3.57
June	3.70
July	3.86
August	3.89
September	4.47
October	3.70
November	3.80
December	4.80
Average	4.21

2.2. Assessment of playing surface characteristics

The Tarkwa Akoon soccer park has been transformed into an Astroturf soccer pitch. The installation of the piezoelectric tiles would only be practicable beneath an artificial Astroturf; one that can be simply removed for maintenance and repair (Claudio 2008). This is quite different from a natural grass field. However, after a 3-year research conducted by FieldTurf (Gosnell et al. 2022), there has been a considerable transition in playing surface material that has started making the move from natural grass to synthetic turf, due to the advantages associated with synthetic Astroturfs which include simple maintenance, less prone to poor weather condition, and less harmful to the park itself (Gosnell et al. 2022).

2.3. Site meteorological data and solar irradiance

The solar radiation of the location is one of the most important considerations when installing PV. Based on the solar irradiation data presented in Table 1, Tarkwa is a relatively sun-rich town

Figure 1. The Akoon soccer park.

Table 2. Load assessment for the Tarkwa Akoon Park.

S/N	Equipment name	Quantity	Power rating (W)	Average daily use (hr/Day)	Energy consumption (Wh/Day)
1	Computer	4	90	5	1800
2	Television	2	150	2.5	750
3	Fans	4	55	3	660
4	Air conditioning	2	500	3	3000
5	Fluorescent light	8	20	5	800
6	Amplifier	2	150	2	600
7	Speakers	4	120	2	960
8	Street light	4	100	12	4800
9	Floodlights	4	75	12	3600
10	Inkjet printer	1	1500	3	4500
11	Photocopier machine	1	183	3	549
Total daily energy consumption					22,019

with a daily average solar irradiance of 4.21 kWh/m ^{2} ('Data was retrieved from the University of Mines and Technology Environmental and Safety Lab, Ghana' 2022). This suggests that solar power systems would work very well in this region. The wet season is cold and mostly cloudy in Tarkwa, and the dry season is hot and partly cloudy all year long.

2.4. Load assessment

The Akoon Park solely depends on the national grid supplier, the Electricity Company of Ghana (ECG) for its electricity. During matches, the energy required is used to power offices, changing rooms, and public address systems, while at night energy is required to power lights to the pitch and outside. Table 2 presents a load assessment for Tarkwa Akoon Park. Based on this load assessment, it is established that Akoon Park utilises 22,019 Wh of energy daily to power the pitch. The pitch is an open cast field; hence football matches are played during the day when there is natural light (the sun). There is a split in energy requirement into night and day activities.

Table 3. Average maximum speed, average distance, average no. of sprints, and average mass of players at their various positions ('World Cup's Top Physical Performances' 2022).

Players at their various positions	Average maximum running speed of players (m/s)	Average distance covered by players (m)	Average No. Sprints by players	Average mass of players (kg)
Centre Back Players	8.31	9100	23	81.3
Fullback Players	8.03	11,600	38	78
Midfielder Players	10.14	10,600	30.5	74
AVERAGE VALUE	8.83	10,430	30.5	78

2.5. Estimation of force exerted by a player during sprinting

To compute the force exerted by players, several assumptions are made based on statistical data from previous sporting events and existing studies (Del Coso et al. 2020; '2015 NFL Scouting Combine' n.d.; 'Pavegen brings kinetic power' 2016; 'Pavegen' 2020; Schimpchen et al. 2015; 'World Cup's top physical performances' 2022). Firstly, to deduce the force exerted by a player the following parameters are taken into consideration: the average number of sprints (S_n), the average distance (d), and the average maximum running speed covered by players (v) (m/s), and the average mass of a player in the various soccer positions (m) in kg. These considerations are adopted based on the statistical analysis of the athletic performance of all the players in their rightful positions (see Figure 2), during the FIFA World Cup Russia 2018 ('World Cup's top physical performances' 2022). Table 3, therefore, presents the data such as the distance covered by each player in every game, the players' maximum running speed during the game, the number of sprints, and the mass of players.

Figure 2. Various soccer positions.

From Table 3, it is established that the average number of sprints, the average distance covered by players, the average maximum running speed covered by players, and the average mass of a player in the various soccer positions are 30.5, 10,430 m, 8.83 m/s, 78 kg, respectively. It is evident in Table 3 that sprinting behaviour differs across the various positions with fullback players performing more sprints compared to the other positions. To ascertain the reasonability of the data in Table 3, Schimpchen et al. (2015) have analysed the sprinting behaviour for 19 matches of the German national team between 2012 and 2014 and found that the average number of sprints of players per game is 17.2 ± 3.9, which agrees with the average number of sprints in Table 3. In another study, Del Coso et al. (2020) have also reported players' maximum sprinting speed ranging from 8.88 to 9.4 m/s, during the Spanish first-division league (La Liga) from the 2017–2018 season. The force per step each player exerts during sprinting is calculated using the average value of the mass of 78 kg in Table 3 and the acceleration of the player sprinting. Before the start of the game, the player has an initial speed of 0 m/s and when the snap signals the commencement of the game, the speed of the player begins to change from low to high. This rate of change in velocity of the player is the player's acceleration (Hamilton, Weimar, and Luttgens 2012), which is given as (Eager, Pendrill, and Reistad 2016):

$$a = \frac{v_f - v_o}{t} \tag{1}$$

where v_f represents the maximum velocity, v_o represents the velocity at a stand-still, and t = average start-up time to reach the maximum speed (sec).

Secondly, for this study, data from the 2015 NFL Scouting Combine's 36.58 metres (40 yards) dash are employed in determining the subsequent approximation ('2015 NFL Scouting Combine' n.d.). The 36.58 metres dash is a numerical value used to assess the speed and acceleration of football players as quickly as possible beginning from a stand-still (0 m/s), which will imply the commencement of a play ('2015 NFL Scouting Combine' n.d.).

Assuming that a professional player reaches their top speed before the 36.58 m dash, they maintain maximum speed until the end of the game. McFarlane (1993) has categorised the rate of acceleration of players in motion (sprinters) during the 36.58 m dash and deduced that players in motion attain maximum velocity, or acceleration of 0 m/s^2, at 25 m.

Also, based on the statistical data of the FIFA World Cup Russia 2018 ('World Cup's top physical performances' 2022), presented in Table 3, an average maximum speed of 8.83 m/s can be determined, which is assumed to be the maximum speed at the 25 m marker. According to the 2015 NFL Combine Results ('2015 NFL Scouting Combine' n.d.), the average 36.58 m dash time of all the 313 participants (runners) that took part in the 2015 NFL Scouting Combine was 4.81 s.

Therefore, assuming a 4.81 sec time at 36.58 m dash and 25 m marker at which the highest speed (8.83 m) occurs, the time interval over which the change in velocity occurred can be calculated as:

$$\frac{25}{36.58} \times 4.81 = 3.30 \text{ s}$$

This implies that the player can sprint from a starting speed of 0 m/s to 8.83 m/s in 3.30 s. Therefore, the acceleration of the player running using Equation (1) can now be computed as follows:

$$a = \frac{8.83 - 0}{3.30} = 2.68 \text{ m/s}^2$$

Now, the force in newton (N) per step each player exerts when sprinting/running at 36.58 metres dash is calculated using the average value of the mass of the players (m) (see Table 3) and the acceleration of a player running (a), as follows (Kalhor, Farzaneh, and Kalhor 2020):

$$\begin{aligned} \text{Force per Step} &= m \times a \\ &= 78 \text{ kg} \times 2.68 \text{ m/s}^2 \\ \text{Force per Step} &= 209.04 \text{ newtons per step} \end{aligned} \tag{2}$$

This assumes that a player can produce a force that is 2.68 times their body weight, which will not occur with every step. This force per step will be used in later calculations to determine the total force per player in a game and the corresponding amount of electrical power produced, applying the power produced per step during the Pavegen tile experiment (7 watts per step) ('Pavegen brings kinetic power' 2016; 'Pavegen' 2020).

Furthermore, the number of steps a player takes in a game needs to be determined. It is stated by Frost Valley that a player takes about 195 steps per minute for a busy game and 144 steps per minute for a recreational game, which is equivalent to about 17,550 steps and 12,960 steps for the entire 90 min of play, respectively ('Physical activity: Soccer' n.d.). Since, usually, not all players can exhaust the 90 min full time, an average of 15,255 steps is used in this study for the subsequent analysis. Using the assumed average number of steps 15,255 steps per player and the result obtained in Equation (2), the approximated total force of a player during an entire game is computed as:

$$\begin{aligned} \text{Total Force} &= \text{Force per Step} \times \text{No. of Steps per Player} \\ \text{Total Force} &= 209.04 \frac{\text{N}}{\text{step}} \times 15,255 \text{ steps} \\ &= 3,188,905.2 \text{ N} \\ &= 3.19 \text{ MN} \end{aligned} \tag{3}$$

This implies that approximately 3.13 MN is produced by each player during a match.

2.6. Force per 7-watt Pavegen tile

Herein, assumptions are made in relation to pedestrian's average walking speed using values reported in previous literature studies (Bowman and Vecellio 1994; Chang, Woo, and Wang 2011; Coffin and Morrall 1995; Fordea and Janice 2021; Knoblauch, Pietrucha, and Nitzburg 1996) (see Table 4).

To determine the acceleration of a walking Pavegen player, an estimate of the average walking speed of a pedestrian must be determined. On average, it could be deduced from Table 4 that the majority of pedestrians could walk at a mean speed of 1.35 m/s. As calculated previously, a player can sprint from a starting speed of 0–8.83 m/s in 3.30 s. Knoblauch, Pietrucha, and

Table 4. Mean walking speed of pedestrians of various age groups.

Age group	Mean walking speed (m/s)	Reference
Younger	1.22	Chang, Woo, and Wang (2011)
Younger	1.27	Knoblauch, Pietrucha, and Nitzburg (1996)
Teenagers	1.45	Fordea and Janice (2021)
Middle age	1.45	Fordea and Janice (2021)
Younger	1.47	Bowman and Vecellio (1994)
Adults	1.40	Bowman and Vecellio (1994)
Average	1.35	

Nitzburg (1996) have reported quite similar mean start-up time of 2.50 s. These estimated mean values are used to calculate the acceleration of walking Pavegen players.

From the above assumptions, considering an average expected speed value of 1.35 m/s and an average start-up time of 3.30 sec to reach that speed, the rate of acceleration of a moving Pavegen player is computed using Equation (1):

$$a = \frac{1.35\frac{\text{m}}{\text{s}} - 0\frac{\text{m}}{\text{s}}}{3.3\text{ sec}}$$

$$a = 0.4\text{ m/s}^2$$

Pavegen demonstrated that about 7 W of power generated during every walking pace was the outcome of a footstep pressure exerted by a 68.04 kg Pavegen player ('Pavegen brings kinetic power' 2016). Although this power value may vary depending on the weight of the step. Therefore, with a maximum average speed of 1.35 m/s, the force per step of each Pavegen player is calculated as follows, using Equation (4):

$$\begin{aligned}&\text{Force per Step of Pavegen Player}\\&= \text{Mass} \times \text{Acceleration of a Moving Paevegen Player}\\&\text{Force per Step of Pavegen Player}\\&= 68.04\text{ kg} \times 0.4\text{ m/s}^2\\&= 27.22\text{ newtons per step}\end{aligned} \tag{4}$$

So, it can be deduced that a walking Pavegen player exerts a force of 27.22 newtons per step. Also, to generate 7 W of power per each step, as stated by Pavegen ('Pavegen brings kinetic power' 2016), the force per power is calculated using the approximate equation:

$$\text{Force per power} = \frac{\text{Force per step of Pavegen Player}}{\text{7 watts per step of Pavegen Player}} \tag{5}$$

$$\text{Force per power} = \frac{27.22\text{ N}}{\text{step}} \times \frac{\text{step}}{7\text{ W}}$$

$$= 3.89\text{ newtons per watt}$$

It is therefore secure to state that 27.22 newtons of force generates 7 watts of energy or 3.89 newtons per watt.

2.7. Number of steps of spectators

Another way of harnessing kinetic energy through footfall may be through the spectators or fans that attend the game. Should sporting facilities lay down strips of piezoelectric tiles across the stadium entrances, constant kinetic energy can be harvested as spectators troop in and out of the pitch. To calculate the amount of energy produced from spectators' footsteps, the approximate number of spectators that attend a game has to be determined. The average pitch capacity of the Akoon soccer pitch is approximately 10,000. The number of footsteps of spectators can then be estimated using the dimensions of a piezoelectric tile 0.599 m by 0.434 m (Elhalwagy, Ghoneem, and Elhadidi 2017). Supposing each spectator enters and exits the pitch at a walking pace, it is secure to mention that each spectator will step on the 0.599-meter piezoelectric tile strip twice during a day's match. Considering about 10,000 spectators stepping on tiles two times during a game, we can assume a total of 20,000 steps on the piezoelectric tiles a day.

2.8. Component sizing

2.8.1. Pitch size based on piezoelectric tile installation, area, and number of tiles

For the piezoelectric harvesting system, a portion of the pitch is considered. In this consideration, the 18-yard boxes and goalposts of both sides of the pitch are excluded because players make less movement on these regions of the field; other possible alternatives are the centre of the pitch and its entrance which are active zones for players and fans' movements, respectively. As shown in Figure 3, the portion of the pitch used for the installation of the piezoelectric tiles is the centre circle with a radius from the halfway line, since it is an active zone for player movements while trekking or running, and its area is calculated in Equation (6). Considering the radius dimension of the region for piezoelectric installation from Figure 3, and the dimensions of a piezoelectric tile, the number of tiles can be computed as follows:

Area of the centre circle (A_{cc}) (Cox and Lo 2019):

$$A_{cc} = \pi r^2 \tag{6}$$

Using the radius of the centre of the field 9.15 m;

$$A_{cc} = \pi (9.15)^2$$

$$A_{cc} = 263.0\text{ m}^2$$

Also, using the piezoelectric tile dimensions (Length = 0.599 m and breadth = 0.434 m) (Elhalwagy, Ghoneem, and Elhadidi 2017), the area of the piezoelectric tile is calculated using the following.

Area of the tile (A_t) (Cox and Lo 2019):

$$\begin{aligned}A_t &= \text{Length} \times \text{Breath}\\A_t &= 0.599 \times 0.434\\A_t &= 0.26\text{ m}^2\end{aligned} \tag{7}$$

Using the results obtained in Equations (6) and (7), the number of tiles (N_t) is calculated as follows:

$$N_t = \frac{A_{cc}}{A_t} \tag{8}$$

$$N_t = \frac{263\text{ m}^2}{0.26\text{ m}^2}$$

$$N_t = 1012\text{ tiles}$$

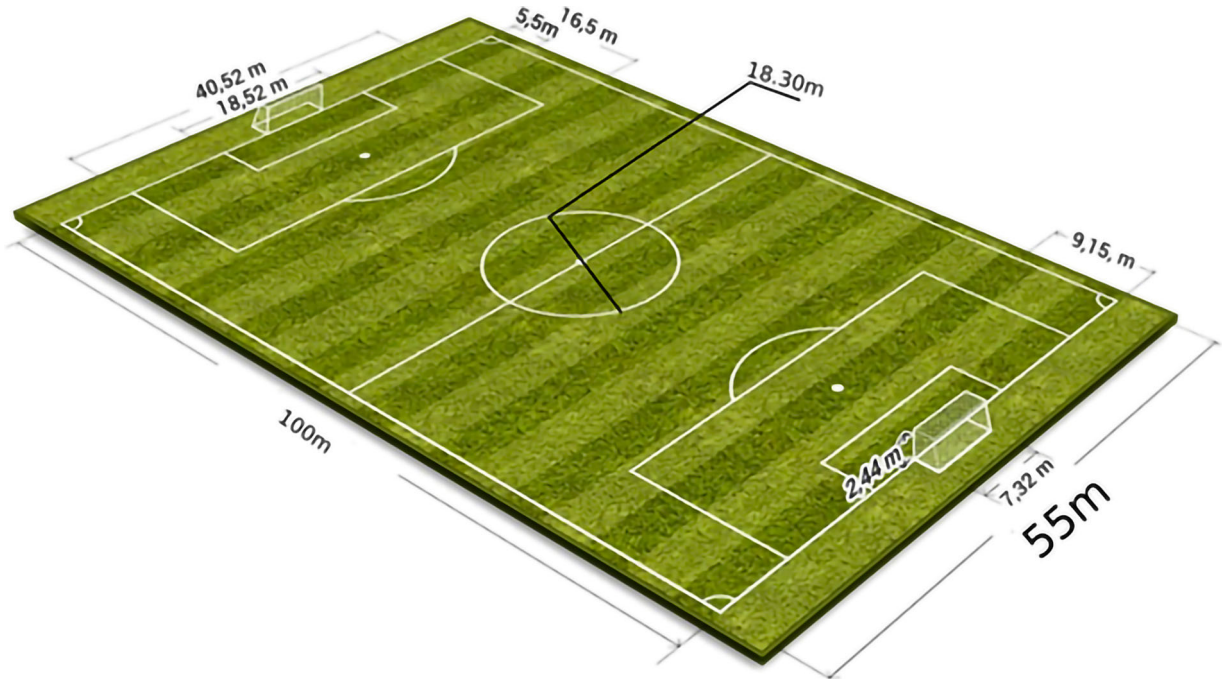

Figure 3. Field showing the piezoelectric installation region.

2.8.2. Photovoltaic system sizing concept

In the module sizing for this system, the basic parameters to consider are the daily load requirements of the facility, total power needed to be produced from modules, photovoltaic (PV) module selection, the number of modules needed, series and parallel PV strings calculations, PV layout and mounting. The standard parameters to consider are the peak sun hours and the system efficiency. The resultant values are shown in Figure 4.

2.8.3. Summary of components sizing

Table 5 presents a summary of all the materials or components and their corresponding parameters and specifications used for the design.

2.9. Design concept

2.9.1. Block diagram

A simple block diagram of the proposed design for the hybrid electricity generation using solar energy (solar PV) and kinetic energy of players' footfall harnessed by piezoelectric tile is shown in Figure 5.

2.9.2. Proposed design

The Tarkwa Akoon soccer field is to be converted into a high-tech football pitch. Approximately based on calculations (see Equation 8), 1,012 energy-capturing piezoelectric tiles will be able to harness the movement of players to generate electricity. Installed along with solar panels, the player-powered piezo tiles will be able to supply electricity to the pitch and neighbouring surroundings. As stated previously, the design is such that the installation of the piezoelectric tiles is underneath a synthetic Astroturf at the centre circle for easy removal during maintenance and repair. The various views of the proposed design are made possible using AutoCAD software. Figure 6 shows the segregated view of the piezoelectric system components beneath the Astroturf.

Also, Figure 7 shows the exploded view of the piezoelectric system design. It consists of the two electrodes (top and bottom electrodes) that sandwich the piezoelectric cantilever and a quartz tile. Quartz is used for the piezoelectric substrate due to its luminous piezoelectric properties, first discovered by the Curie brothers (Azimi et al. 2020). Quartz is among the materials that naturally harness an electrical charge from mechanical stress. The tip or seismic mass exerts a downward force which contributes to causing a strain on the electrodes. When the environmental excitation frequency is the same as the self-frequency of the piezoelectric cantilever, the beam resonates inducing an emf on opposite parts of the plate from the region of higher potential that is the cover plate to the region of low potential (the bottom electrode). Moreover, the solar panels are mounted on the shed of the Very Important Person (VIP) seating and the roof of the ticket office. Figure 8 shows the side view of the proposed solar PV mounting.

3. Results and discussion

3.1. Energy generated

In an assumption that a pre-determined number of 209.04 newtons per step (see Equation 2) is produced by a player, and the rate of 3.89 newtons (see Equation 5) is required to produce 1 watt of energy, a one-step rate of the player can now be calculated by dividing the result obtained in Equation (2) by the one obtained in Equation (5) as:

$$\frac{209.04\ \text{N}}{\text{step}} \times \frac{\text{watt}}{3.89\ \text{N}} = 53.74\ \text{watts per step}$$

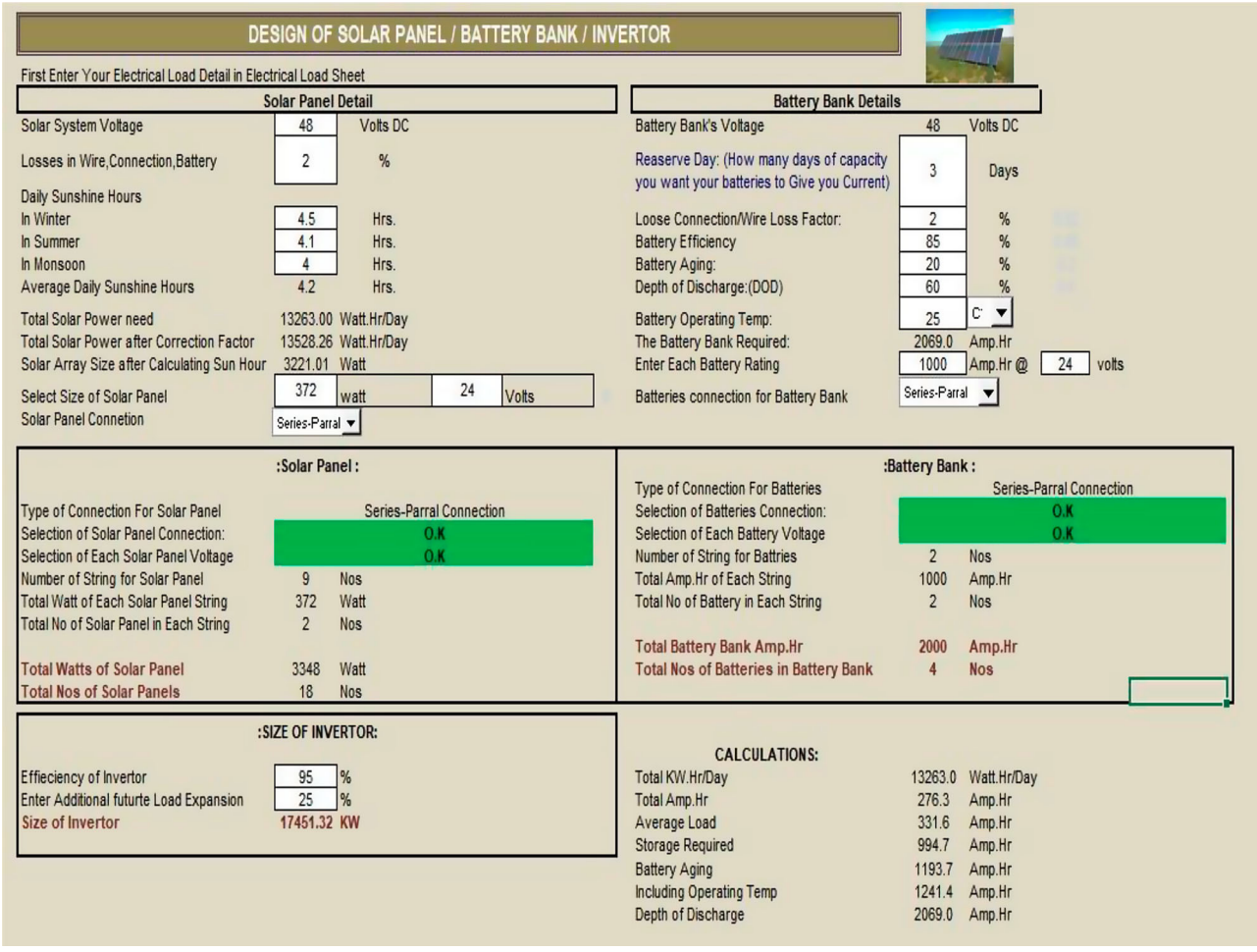
DESIGN OF SOLAR PANEL / BATTERY BANK / INVERTOR
First Enter Your Electrical Load Detail in Electrical Load Sheet
Solar Panel Detail
Solar System Voltage 48 Volts DC
Losses in Wire,Connection,Battery 2 %
Daily Sunshine Hours
In Winter 4.5 Hrs.
In Summer 4.1 Hrs.
In Monsoon 4 Hrs.
Average Daily Sunshine Hours 4.2 Hrs.
Total Solar Power need 13263.00 Watt.Hr/Day
Total Solar Power after Correction Factor 13528.26 Watt.Hr/Day
Solar Array Size after Calculating Sun Hour 3221.01 Watt
Select Size of Solar Panel 372 watt 24 Volts
Solar Panel Connetion Series-Parral
Battery Bank Details
Battery Bank's Voltage 48 Volts DC
Reaserve Day: (How many days of capacity you want your batteries to Give you Current) 3 Days
Loose Connection/Wire Loss Factor: 2 %
Battery Efficiency 85 %
Battery Aging: 20 %
Depth of Discharge:(DOD) 60 %
Battery Operating Temp: 25
The Battery Bank Required: 2069.0 Amp.Hr
Enter Each Battery Rating 1000 Amp.Hr @ 24 volts
Batteries connection for Battery Bank Series-Parral
:Solar Panel :
Type of Connection For Solar Panel Series-Parral Connection
Selection of Solar Panel Connection: O.K
Selection of Each Solar Panel Voltage O.K
Number of String for Solar Panel 9 Nos
Total Watt of Each Solar Panel String 372 Watt
Total No of Solar Panel in Each String 2 Nos
Total Watts of Solar Panel 3348 Watt
Total Nos of Solar Panels 18 Nos
:Battery Bank :
Type of Connection For Batteries Series-Parral Connection
Selection of Batteries Connection: O.K
Selection of Each Battery Voltage O.K
Number of String for Battries 2 Nos
Total Amp.Hr of Each String 1000 Amp.Hr
Total No of Battery in Each String 2 Nos
Total Battery Bank Amp.Hr 2000 Amp.Hr
Total Nos of Batteries in Battery Bank 4 Nos
:SIZE OF INVERTOR:
Effieciency of Invertor 95 %
Enter Additional futurte Load Expansion 25 %
Size of Invertor 17451.32 KW
CALCULATIONS:
Total KW.Hr/Day 13263.0 Watt.Hr/Day
Total Amp.Hr 276.3 Amp.Hr
Average Load 331.6 Amp.Hr
Storage Required 994.7 Amp.Hr
Battery Aging 1193.7 Amp.Hr
Including Operating Temp 1241.4 Amp.Hr
Depth of Discharge 2069.0 Amp.Hr

Figure 4. Graphical user interface for solar panel, inverter, and battery sizing.

Table 5. Summary of component sizing.

Material	Parameters	Specification
Solar PV	Load	13,262 Wh
	System size	2254.71
	System voltage	48 V
	System current	46.973 A
	Total number of panels	12
Piezoelectric	Power produce per tile	7 W
	Total number of tiles	1012
	Power produced by total number of tiles	7084 W
Inverter parameters	Inverter capacity for solar PV	18 kVA
	Inverter current for piezoelectric tiles	14 kVA
	Number of inverters	2
Charge controller	Controller Rated current /capacity	60 A
	Number of a charge controller	1
Storage system	Total number of batteries	12
	Individual battery capacity	1000 Ah

Therefore, it is assumed that approximately 53.74 W is generated from each step of a player. Since the number of steps taken by a player in a game is already given as 15,255 steps (see Equation 3), one can anticipate a total power of (15,255 steps $\times$ 53.74 watts $=$ 819,803.7 watts) or 819.8 kW to be produced by each player during a soccer game. Furthermore, considering the scenario in relation to spectators that attend a day's game (see section 2.7), using Pavegen's rate of 7 watts per step of a walking Pavegen player, the energy produced from a spectator's footsteps during a game is about 14 watts or 0.014 kW since each spectator is assumed to step on the piezoelectric tile strip twice during a day's game. Figure 9 shows the power generated and number of steps plotted as functions of the participants (a player and a spectator) during a day's game using Excel spread sheet.

The results in Figure 9 imply that if the Tarkwa Akoon soccer pitch is to install only piezoelectric tiles underneath the Astroturf at the centre of the park, with the assumption that 22 players are on the field, approximately 18 MW of power could be generated. However, the piezoelectric system is reliant on footsteps frequency which is only essential during game day operations. It is established that during pre-and post- events, a total game day operation usually amounts to about 90 min (1.5 h) of energy usage. Meaning, with piezoelectric harvesters, the stadium can produce a total of about 27 MWh of energy from players' footsteps. This seems to be one of the most cost-effective utilisations of piezoelectric tiles; since fewer tiles are required to capture players' footsteps. This will also limit the challenges associated with maintenance and labour when installed underneath the Astroturf. This result agrees with those presented in earlier studies by other researchers (Mota and Barroso 2021). Some scientists have presented simulation models (Mota and Barroso 2021; Najini and Muthukumaraswamy 2017; Vázquez-Rodríguez et al. 2019), assessing the effects of huge vehicular traffic on paved paths. There is a possibility for a system having 30,000 piezoelectric crystals to generate about 65.00 MWh of energy per

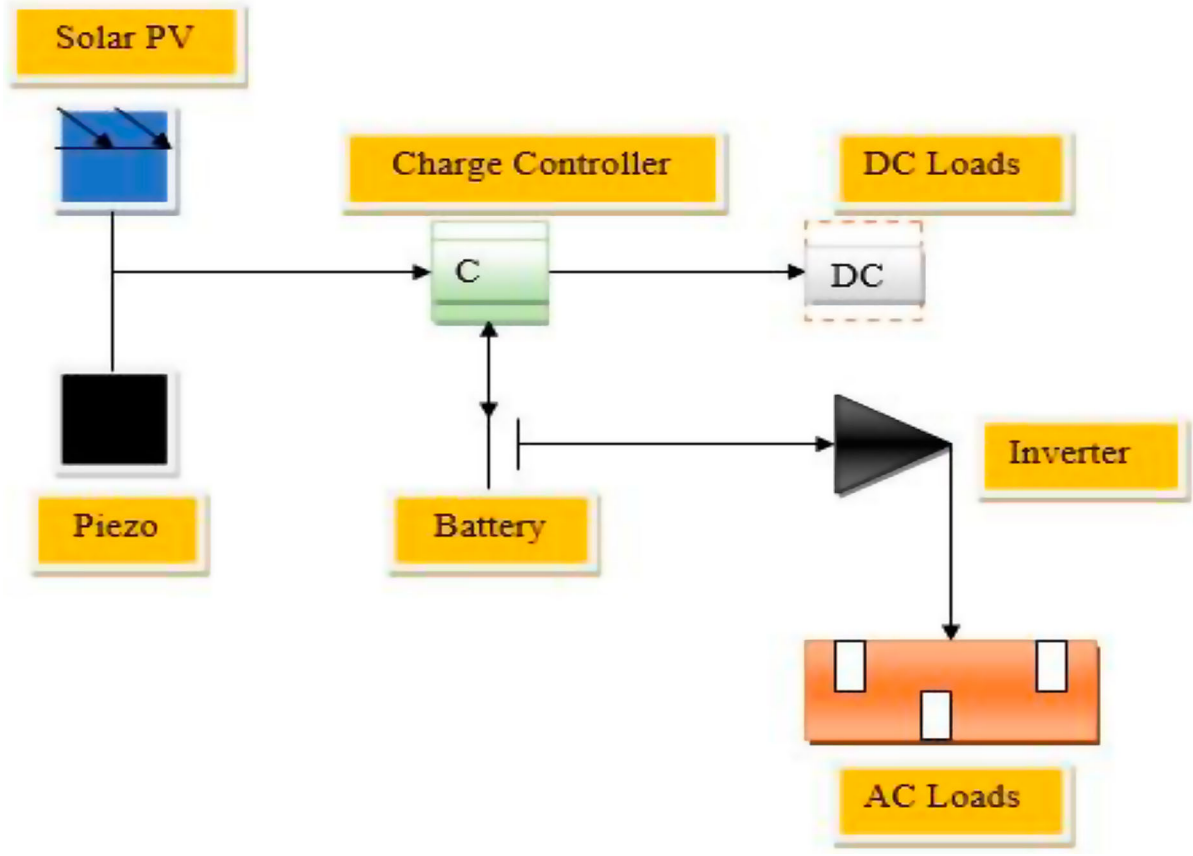

Figure 5. Simple block diagram of a hybrid solar PV and piezoelectric system.

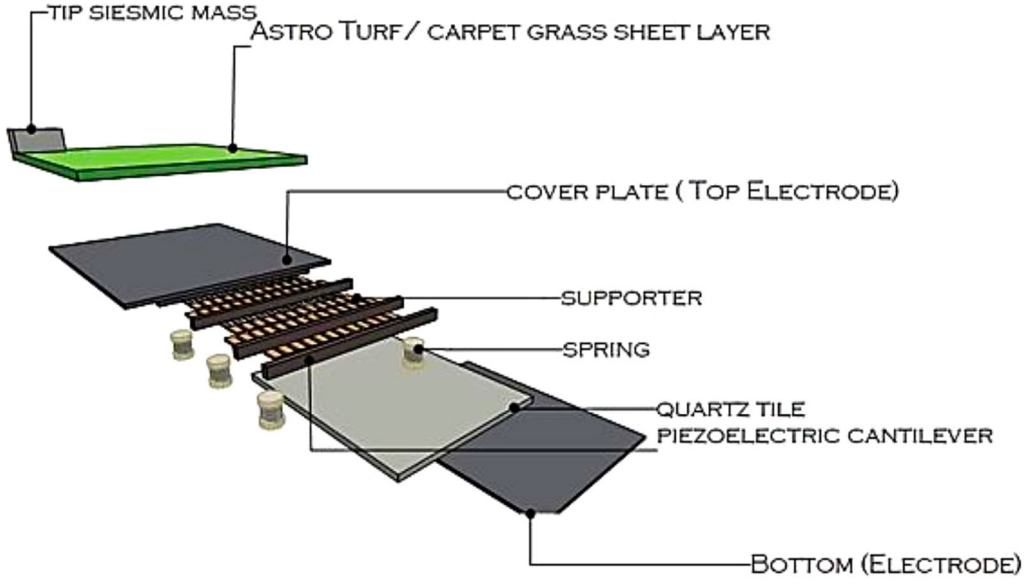

Figure 6. Segregated view of the piezoelectric system beneath the Astroturf.

year (Moure et al. 2016), and up to approximately 306.37 MW of power using the same number of piezoelectric crystals with a traffic volume count of 600 vehicles per hour (Mota and Barroso 2021).

Also, from Figure 9, it can be deduced that for a normal game day operation, the 10, 000 spectators can produce about 140,000 W which is equivalent to 210 kWh of energy. So, if the Akoon soccer pitch were to install piezoelectric tiles underneath the Astroturf and at the entrances of the pitch, one can anticipate a total power of about 18.14 MW or 27.21 MWh. Despite the number of spectators on the Akoon soccer pitch, the players in total produce more energy than the spectators during a game due to the greater frequency of players' footsteps. This is so because the number of steps taken by each player is about 7,600

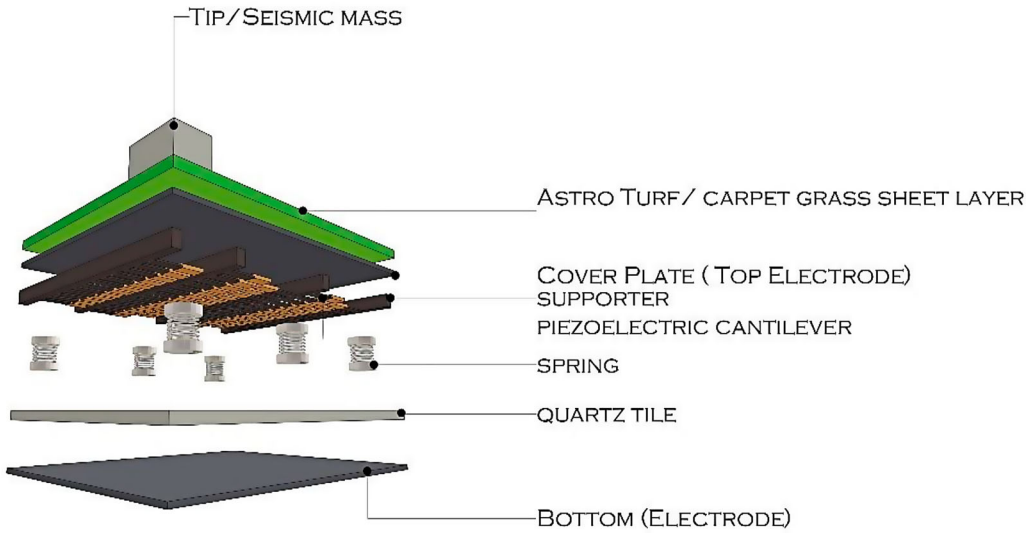

Figure 7. An exploded view piezo-Astroturf design.

Figure 8. Side view of the solar PV mounting design.

times more than the number of steps by each spectator during a game. Similarly, the maximum average speed of a player sprinting is about 6.5 times more than the average walking speed of a spectator on a pitch. However, using similar technology, several existing studies have reported extremely low power output values. For instance, Shanmugam et al. (2020) have deduced that when a weight of 75 kg is applied to a piezoelectric tile, a very low peak power of 4.5 W is generated. Saifan et al. (2019) have also reported an extremely lower energy value of 0.045 W whenever a pedestrian steps on a sidewalk. In another study, using a different harvesting technology – the non-piezoelectric technology, Ang et al. (2019) have experimentally and theoretically reported extremely low values of power ranging from 0.18 W to 0.29 W. These values are far lower than the results obtained in this study.

From Figure 4 in section (2.8.2), it is deduced that solar PV can produce about 3,221 W of power every day, which is approximately 13.263 kWh of energy. These compared with the above deductions indicate a substantial difference in energy output from piezoelectric technology versus those generated by solar PV. Therefore, by installing piezoelectric tiles used for harvesting energy from players' footsteps along with solar PV, the hybrid configuration will be able to supply a total power of 27 MW (40.50 MWh) during a 90-minute game, to the park and neighbouring surroundings. Furthermore, a hybrid system consisting of piezoelectric tiles used for harvesting energy solely from spectators' footsteps and solar PV will generate about 143.22 kW (214.83 kWh) of energy per game. This analysis, therefore, paves the way for the two technologies to supply the load separately or at the same time depending on the availability of the energy

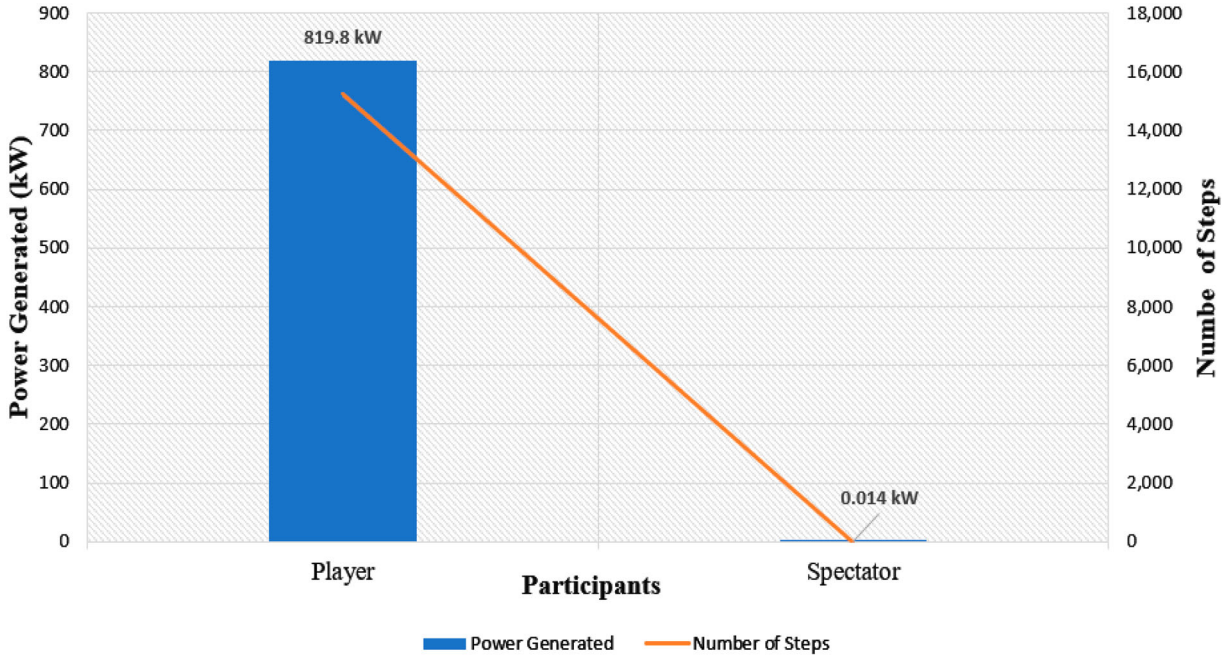

Figure 9. Power generated by a player and a spectator and their corresponding number of number steps.

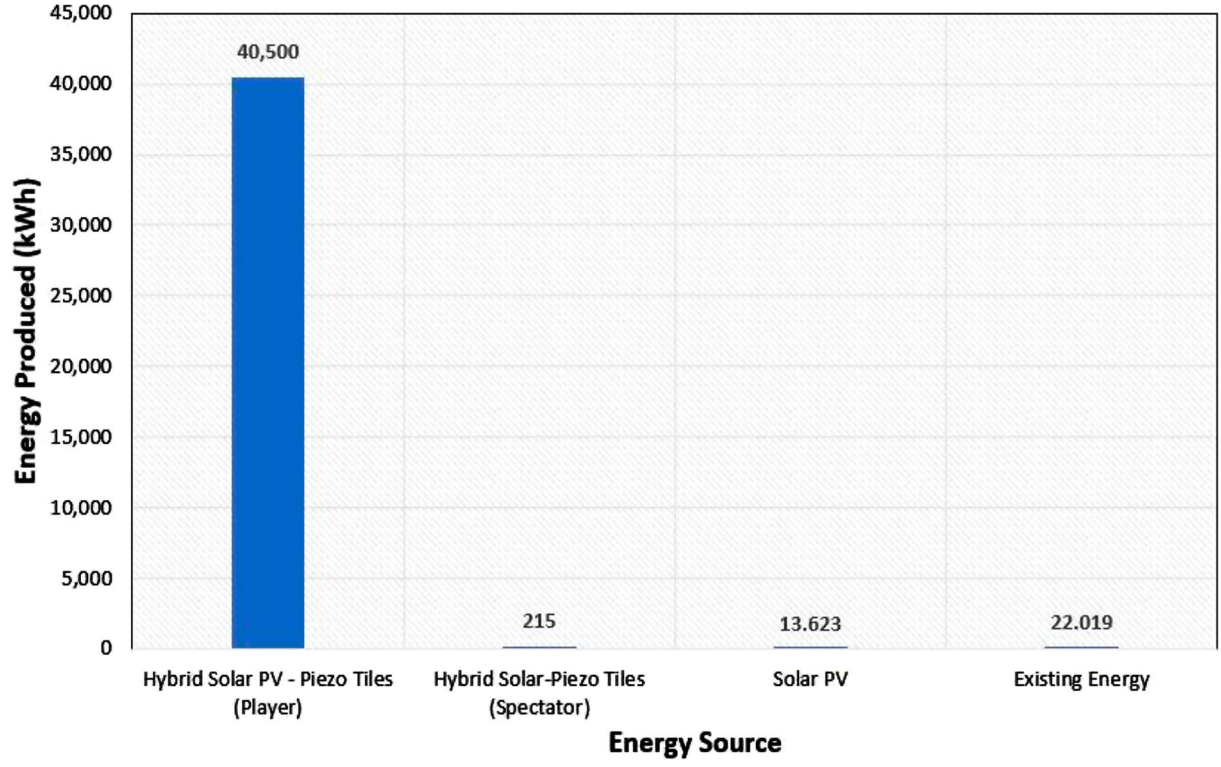

Figure 10. A graph showing the energy produced versus the corresponding energy sources.

sources. The analysis here agrees with that presented by Mahajan et al. (2017), who have reported that a hybrid piezoelectric-solar system could generate power of about 1 MW when the piezoelectric floor tiles and solar panels are properly designed with the right specifications. Figure 10, shows the energy generated plotted as a function of the various energy sources which include hybrid solar PV-player-powered piezo system and spectators-powered counterpart, and the solar PV together with the existing energy consumption of 22.019 kWh (see Table 2).

It could be deduced from Figure 10 that the piezoelectric harvesting system can solely power the entire pitch and its surrounding neighbours; implying that a hybrid combination of both harvesters can produce a substantial amount of power. Contrary to solar PV, which is limited to daylight periods and peaks around midday, energy from piezoelectric tiles can be generated continuously provided there are players sprinting and spectators moving in and out of the pitch. This implies that these technologies can be used separately or combined depending on

the electric power requirement, the weather condition as well as the presence of human footsteps. Govind et al. (2015) have investigated the feasibility of using piezoelectric tiles and solar panels to generate useful electricity, and have confirmed that a combination of these technologies is very efficient.

Using the results in Figure 10, it can be established that by implementing piezoelectric tiles used for harvesting energy from players' footsteps, higher energy savings of about 99.94% is realised. However, using only solar PV technology will result in negative or zero energy savings, since the overall energy consumption of the pitch is more than the energy generated using solar PV only, hence a hybrid system is feasible. In terms of a hybrid system, approximately 99.94% of energy is saved using both piezoelectric tiles and solar PV simultaneously; depicting comparatively higher energy saving to the soccer park during match day operations. Meanwhile, installing spectator-powered piezoelectric tiles together with solar PV will save about 89.75% of energy per day. This shows that using the player-powered piezoelectric tiles produces more energy than the spectator-powered tiles. This also reveals that with little use of solar panels, maximum power can still be produced using piezoelectric tiles. The results of this study agree well with the 99.3% and 99.9% energy savings reported by Moussa, Ismaeel, and Solban (2022) upon utilising Sustainable Energy Floor (SEF) piezoelectric tiles and Waynergy piezoelectric tiles, respectively, for energy generation in public buildings in Egypt. In a related study, Saifan et al. (2019) have also revealed that installing piezoelectric tiles on the University of Jordan's Primary gate could save approximately 91% of energy per day when 18,318 students step on it. Moreover, Moussa (2020) has reported that the installation of piezoelectric tiles in children playing area produced energy greater than 50% of the existing energy use in the sports club.

Clearly, the hybrid piezoelectric-solar PV system presented in this study has a number of advantages over previously reported energy harvesters (Ang et al. 2019; Mota and Barroso 2021; Moure et al. 2016; Najini and Muthukumaraswamy 2017; Saifan et al. 2019; Shanmugam et al. 2020; Vázquez-Rodríguez et al. 2019). It generates very high output electrical energy and can be used for large-scale applications.

3.2. Practical applications and contributions of the research

The implementation of piezoelectric generators is feasible when installed at areas where the highest pressure is realised so that maximum stress through walking is employed, and perhaps be converted into optimum amount of electricity. For instance, areas where greater frequency of vehicular movement and higher foot traffic occur. Airports, shopping malls, roads, railway tracks, schools, train stations, etc. are the most common places for these conditions. In terms of large-scale applications, roads, highways, and railway tracks are possible. Traffic situations on roads and highways differ all through the day; there is huge traffic in the morning than at night. In a previous study, Najini and Muthukumaraswamy (2017) have presented a piezoelectric electricity generation system and its techno-economic analysis to support the idea of electricity generation from road traffic using MATLAB-Simulink. The system enhances vehicle performance since it uses kinetic energy released from vehicle movement into useful electricity. The railroad track is one other area for producing a large amount of energy using piezoelectric generators since a high amount of pressure is exerted by trains on the railroad tracks (Hosseinkhani et al. 2021). However, as already stated, the piezoelectric technology hugely relies on footsteps frequency which is only essential during game day operations. Alternative harvesting technologies such as solar PV and wind turbines are harnessed year-round on the earth's renewable resources which are unlimited, and bring about a more consistent energy yield.

By implementing piezoelectric harvesters in sports facilities, renewable energy can be harvested from human motion using the constant footsteps of players and a large number of spectators: the roar produced by spectators during a game and the significant amount of force generated by players. Promising technologies like piezoelectric tiles, can generate huge energy and optimise savings for the sports complex; and could be an indicator for shifting both the building sector and society towards the direction of sustainable development. Apart from the piezoelectric technology, the soccer pitch also uses solar PV installed on the roof. Using these two technologies, we will be able to generate electricity not only during the day but also at night with the help of piezoelectric tiles (Arnab et al. 2014). By utilising these two technologies together, electricity will be generated throughout the year without relying on other sources. The hybrid piezoelectric-solar PV, therefore, offers smart solutions to provide uninterrupted green energy generation and substantially reduce carbon footprint.

3.3. Limitations of the research

The greatest challenge associated with this study is the dependence on several assumptions and estimations. Data was gathered from several sources and research works to find conservative approximations that were not solely verified. Furthermore, this work was conducted from the activity level of soccer players; there would be a variation of results should one consider other sports and physical activities that take place in other sports complex such as track and field stadiums, baseball stadiums, swimming pools, and Indoor arenas.

3.4. Further research directions

The promising feature of this hybrid piezoelectric tile-solar PV system provides room for further research. In the future, researchers can focus on the shock absorbance of the piezoelectric materials that are installed beneath the Astroturf. Moreover, further research can be conducted on the entire product; the kind of piezoelectric crystals, the kind of circuitry that should be placed at the output terminals, and the individual placements of piezo sensors must be considered. Knowledge of the individual components of the entire product would be helpful in maximising the output power from footsteps. Also, regarding solar PV, the type of solar cell and associated photovoltaic materials must be considered in the future. Furthermore, the cost associated with installation, labour, planning, productivity losses, or costs of an entire field project could be a subject of future research.

4. Conclusions

A hybrid kinetic and solar energy harvesting system has been designed to satisfy the load demand of Tarkwa-Akoon Park and part of its environs. A theoretical analysis has been conducted regarding the energy generated using a single source (either solar PV or piezoelectric tiles) or a hybrid configuration of both sources. Implementing player-powered piezoelectric technology alone can produce about 1.23 MWh of energy per player, which is equivalent to a total of 27 MWh considering the footsteps of 22 players on the pitch. Solar PV can also produce approximately 13.263 kWh of energy, with a hybrid player-powered Piezo-solar PV combination producing about 27 MWh of energy. It was also realised that installing piezoelectric tiles at the entrances of the pitch for spectator use, together with solar PV could generate about 214 kWh of energy. This shows that these two technologies can be used separately or simultaneously depending on the electrical energy requirement, the weather condition as well as the presence of human footsteps.

A separate analysis depicts that the energy generated by the 22 players on the pitch is much greater than that generated by the 10,000 spectators during a game. This is so because of the number higher number of steps and high maximum sprinting speed associated with the player-powered piezoelectric tile technology as compared to the spectator-powered counterpart. In terms of energy savings, it was also found that the energy saving of solar PV was as minimal as zero compared to a tremendously higher energy savings of 99.94% associated with the piezoelectric technology using players' footsteps only, implying a 99.94% saving when using both player-powered piezo tiles and solar PV simultaneously. Also, 89.75% energy saving was realised when utilising a hybrid combination of solar PV and spectator-powered piezoelectric tiles at the entrances of the pitch. The hybrid Piezo-PV system possesses low production cost and can be used for large-scale electricity generation. It can supply the building complex, in sports especially and the neighbouring surroundings with an alternate source of energy to help reduce the high global energy demand and eventually decrease the effects of global warming.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Data availability statement

The data that supports the findings of this study are available upon reasonable request

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